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MICRO SAINT MODEL OF FATIGUE ASSESSMENT

ANNUAL REPORT

JONATHAN FRENCH

JANUARY 14, 1992

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Opportunities for fatigue-related accidents are greatest when extended duty cycles must be maintained. A means to plan for the influence of fatigue would be useful to best utilize crew resources. An equation was derived that predicts performance degradation associated with fatigued cognitive abilities. During a 30 hour sleep deprivation study, 9 male subjects were required to perform a 45 minute performance battery every 120 minutes and variables sensitive to fatigue were determined. Plasma melatonin levels also were obtained. Composite response time and accuracy scores were then derived. The equation that best described the composite scores included a linear component (hours awake weighting) and a circadian component (melatonin weighting). The respective prediction equations accounted for 36.7% and 36.9% of the variance in response time performance and 12.4% and 19.9% of the accuracy performance (p .001) These percents indicate that accuracy predictions were more enhanced by the circadian component than were those for response time. This work represents a mathematical description of fatigued performance that is sensitive to circadian cycles and requires minimal input data. The results might be used to recommend when additional crew should be employed as performance

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19. ABSTRACT (continued)

falls below critical thresholds or the best crew rest times during sustained operations.

FOREWORD

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X For the protection of human subjects, the investigator(s) have adhered to policies of applicable Federal Law 45CFR46.

X In conducting research utilizing recombinant DNA technology, the investigator(s) adhered to current guidelines promulgated by the National Institutes of Health.

Jan French 12 Dec 1991

PI Signature Date

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Micro SAINT Model of Fatigue Assessment
ANNUAL REPORT 1991

Introduction

There is an increasing need for extended and atypical duty schedules in both civilian and military situations. For example, shift work and compressed work week schedules are finding increased application in industry. As well, the accelerated pace of the recent Gulf War involved routinely long duty days and 24 hour operations. Correspondingly, there are more opportunities for fatigue related accidents when long or unusual duty cycles must be maintained. In fact, some of the greatest technologically based catastrophes like the release of methylisocyanate in Bhopal India or the Chernobyl nuclear disaster in the Soviet Union can be linked to human errors made by crews not completely adjusted to an early morning shift. Figure 1 demonstrates the increase in vehicular accidents during the early morning hours when fatigue is greatest. A means to plan for the influence of fatigue on performance would be useful to best utilize human resources. The purpose of this report is to describe a mathematical model that is designed to predict performance degradation associated with sustained performance and a computer simulation of complex cognitive performance which makes use of the model.

Systems analytical models like MicroSAINT are used to develop computer simulations of human performance in clearly defined situations with varying degrees of workload and complexity. These models are restricted in their usefulness since they do not consider operator fatigue in the performance simulations. In fact, most models are idealized simulations that seldom make mistakes and are unaffected by ordinary human foibles like lapses in attention. The mathematical model was developed to ameliorate this deficiency and permit the impact of fatigue on computer simulations of human performance to be estimated. A MicroSAINT computer simulation of tasks performed by a weapons director on an AWAC aircraft was selected as the model to be degraded by the equation. The task involves a complex and highly organized behavior that is affected by prolonged duty and circadian dysrhythmia. However, the fatigue model was designed to be parsimonious and applicable outside of computer simulations as well. For example, managers could estimate the percentage decay in awareness from a general knowledge of the fatigue equation and staff the most affected shifts accordingly.

METHODS

During the first year of the project an experiment was conducted that evaluated the effects of prolonged duty (30 hours) on cognitive performance measures. During the study, 9 male subjects were required to perform a 45 minute standard tri-service performance assessment battery every 120 minutes. Subjects received training trials over a 10 hour period beginning at 1000 on

the computer battery. At 1800 hours, the study trials began and lasted until 1000 the following day. In addition, EEG, EOG, blood samples and oral temperatures were taken. Primary interest concerned the cognitive skills degraded by fatigue as measured by the performance battery. During the second year of the project, tests sensitive to fatigue were determined by using paired t-tests to compare baseline performance (an average score obtained between the 1800 and 2000 hour performance trials) to every 2 hour performance block. Tests that showed a significant difference from baseline at any of the 120 minute time points were used. The variables from these tests that were significant were categorized as accuracy or response time variables. Finally, the scores were normalized (percent change from baseline score) and included in a composite accuracy or response time scores. Figure 2 shows the decrease in accuracy and the increase in response time associated with the composite scores.

Many attempts were made to mathematically define the performance curves that were generated. Multivariate equations were generated that included eye blink and oral temperature but only a linear decay function demonstrated predictability. In addition, the model lacked a variable that could account for circadian dysrhythmia, such as that which occurs during atypical or extended work periods. Finally, during the third quarter of the project's second year, the neuroendocrinological data became available and melatonin values were considered as a means to permit the equation to have a circadian sensitivity. Figure 3 shows the normal melatonin values that were generated in the fatigue experiment. By comparing Figures 2 and 3, it can be seen that the slope of the performance degradation is greatest between 14 - 20 hours awake which corresponds to the normal nocturnal surge in plasma melatonin levels shown in Figure 3. Melatonin follows a circadian pattern that parallels the human sleep wake cycle. In fact, ingestion of melatonin is reported to induce fatigue in rested individuals. Accordingly, melatonin values were fitted to the equation for composite accuracy (Eq1) and composite response time (Eq2).

(Eq1) Accuracy Performance Score = Y + H(HA) + M(CV)
Where Y = Y intercept (148.3);
H = Hours Awake weight (-2.69107);
HA = Hours Awake (range between 12 - 30 hours);
M = Melatonin weight (-0.54794);
CV = Circadian value (values from Figure 3).

For the values determined for response time, the values are:

(Eq2) Response Time Performance Score = Y + H(HA) + M(CV)
Where Y = Y intercept (81.6);
H = Hours Awake weight (1.23);
HA = Hours Awake (range between 12 - 30 hours);
M = Melatonin weight (0.0139);
CV = Circadian value (values from Figure 3).

Estimates of the variance accounted for (R^2) for the linear description of the composite accuracy scores was 12.4 % whereas with the inclusion of the melatonin weighting this value increased to 19.9%. These results are shown graphically in Figure 4. Figure 4a shows a linear component alone fitted to the composite accuracy score and Figure 4b shows the equation (Eq1) which includes the melatonin weighting. As well, the R^2 for composite response time variability was increased from 36.7% considering only the linear component to 36.9% with the melatonin weighting. Again, these results are shown graphically in Figure 5a and 5b. These percents indicate that accuracy predictions were more enhanced by the circadian component (12.4% vs 19.9%) than was response time (36.7% vs (36.9%). In each case however, a significant ($p<.001$) proportion of the variability was associated with the performance predictions. Use of the melatonin data had the additional advantage of incorporating a circadian component to the equations and served to decelerating the linearly accelerating estimate line as the melatonin values waned. Appendix 1 shows the changes in R^2 for accuracy and response time variables considering all time points and then excluding later time points. Overall, R^2 is greater as hours awake is increased. Correspondingly, less variance is accounted for during the early time points, presumably when subject variability would be greatest.

Figure 6 demonstrates that saliva may be used as a non-invasive measure of plasma melatonin levels. Blood was taken from subjects in the fatigue experiment at 2 times when melatonin values were expected to be elevated. Saliva samples were taken throughout the entire study for comparison. The melatonin surge can be seen in the saliva in Figure 6 and salivary levels compare favorably with the plasma levels, perhaps delayed by about an hour in the saliva as melatonin extravasates from plasma into the saliva fluid compartment. Although melatonin levels for non-shifted subjects performing sustained work could be expected to have the same values as the subjects used in the fatigue experiment, values forindividuals adapted to shift work would have to be determined. For the purposes of the equations however, melatonin values indicate when the subjective night occurs and when fatigue effects would be at their greatest. Thus if an individual awoke at midnight, during the subjective night, they are more apt to show a greater fatigue a few hours later than if they awoke at 0600, during the subjective day. The equation may account for these day night differences in the estimations by decreasing then increasing degradation respectively, as shown in Figures 4b and 5b.

Table 1 shows an application of the equation for composite accuracy estimations for 2 times, 1800 and 2400 midnight. Thus, knowing the hours a subject has spent awake and whether the time of

interest represents the subject's subjective day or night, performance can be estimated by the equations.

Table 1. Using the equation for composite accuracy (Eq1) the values used to generate predictions of performance for 1800 and 2400 midnight for an average subject.

Predicted Score	Actual Score	Y Intercept	Hours Awake Slope	Hours Awake	Melatonin Slope	Melatonin Value
113.45	100	148.3	-2.7	12	-0.6	4.6
77.29	75.74	148.3	-2.7	18	-0.6	41.14

During the fourth quarter of the 2nd year of the project a complex cognitive performance task was selected for modelling by MicroSAINT. Simple models of performance like those shown in Figure 7 for the serial math test can be degraded by including the equations at key nodes in the network. For example response time might be degraded by applying the equation to the time required for completion of the 'Enter Answer' node in Figure 7. Because of the experience available onsite in AWAC simulation, a model of target selection by a weapons director was modelled in MicroSAINT. A depiction of the model is shown in Figure 8. Details of the model are still being developed but essentially it simulates all the steps taken by a Weapons Director (WD) from identifying an unknown aircraft as friend or foe to committing aircraft resources if necessary. It is much more complex than can be easily shown here. In fact, more of the model is shown in Figure 9 to demonstrate the next level of complexity of the model. The cognitive processes reported to underlie the tests deemed to be sensitive to fatigue from the original fatigue study were obtained from the literature. The location of WD actions that would be most affected by these cognitive processes were identified in the simulation by a WD expert and the response time equation was used in the model to slow down the simulated responses. The result of 20 applications of the MicroSAINT WD simulation at each timepoint is shown in Figure 10 along with the corresponding SEM. For example, after 28 hours awake the responses of the WD slowed from 39% to 43 %. The graph might be visualized as the average result of the performance of 20 WD's in dealing with targets.

Additional refinements to the equations are planned for the third year of the project based on a larger sample size in a similar fatigue/sleep deprivation study. The accuracy of the predictions of the equations will be determined by estimating and then determining the results empirically for performance during 36

hours of sleep deprived performance. Finally, the MicroSAINT WD model will be improved to include accuracy variables. The equations will be made generalizable to any computer simulation and as reference tables for non-computer use.

CONCLUSIONS

This project represents an attempt to mathematically describe the effects of fatigue on performance. It may be the first to address the circadian sensitivity of performance prediction. The only requirements for the equation are knowing how long an individual has been awake and whether it is the subjective day or night. Refinements to the equation will consist of increasing the power of the estimate by adding more data to the normalized prediction line as other sleep deprivation studies are conducted. Predicting performance will be validated by first estimating performance decay and then empirically assessing it.

A range of scores can be predicted for each hour on duty that could outline optimum levels of performance. This information would be useful to predict when human efforts are critically degraded and steps taken to keep performance above minimum. The utility of the equation allows it to be used in systems analytical workstation models and to determine the impact of fatigue on these systems. Finally, results might be used to recommend when additional operators or relief crews might best be employed once individual performance falls below a critical ability. This work represents a mathematical description of fatigued performance, with circadian sensitivity and requires minimal input data. The results might be used to recommend when additional crew should be deployed as performance falls below critical levels during sustained operations. We believe the work is heading in the proper directions towards developing a means to degrade computer simulations. The results may extend to non-computer applications as well in planning for the effects of fatigue on shift workers or preparing for acute sustained operations.

Figures:

APPENDICES

Appendix 1 <u>Reduction in R^2 considering various times in the fatigue estimates</u>

The R^2 values for the linear Hours awake (HA) and the circadian sensitive curvilinear equations HA + Melatonin weighting (MW) for select time points in the fatigue study and the associated probability values (p). The variance accounted for values includes the data up to each Hours Awake indicated.

Hours Awake	Accuracy %	p	Response Time %	p
28				
HA	12.35	0.003	36.7	0.0001
HA+MW	19.94	0.0002	36.96	0.0001
26				
HA	10.72	0.005	35.62	0.0001
HA+MW	18.90	0.0007	35.74	0.0001
24				
HA	14.10	0.0024	34.93	0.0001
HA+MW	21.03	0.0008	34.94	0.0001
22				
HA	13.86	0.0056	30.58	0.0001
HA+MW	22.69	0.0014	30.68	0.0001
20				
HA	12.61	0.0167	16.36	0.006
HA+MW	24.38	0.0028	16.73	0.0214
18				
HA	13.93	0.025	2.51	0.356
HA+MW	29.62	0.003	3.53	0.553
16				
HA	0.46	0.738	3.27	0.367
HA+MW	24.83	0.033	3.37	0.663

Appendix 2 Publications during the quarters

French, J., P. Hannon and G. Brainard. Effects of bright illuminance on human performance and body temperature. Ann. Rev. of Chronopharm., 7, 45-49, 1990.

Slater, T., Neville, K., Whitmore, J., French, J. and S. Schiflett, Electrophysiological Correlates of Performance Improvement by Light Intensity, Proceedings of the Human Factors Society, 1990.

Neville, K., French, J. and Schiflett, S. Human Performance Model of Fatigue, Proceedings of the Human Factors Society, 1990.

Brainard, G., Rollag, M., Hannon, P., French, J. and Storm, W. Effects of bright illumination on plasma melatonin in normal volunteers during sustained performance. Proceedings of the Vth Colloquium of the European Pineal Study Group. p 105., 1990

Brainard, C., Hannon, P., French, J. and Storm, W. Effects of bright illumination on plasma cortisol during sustained performance. (Proc. Soc. Light Treatment of biological Rhy., NY, 1990)

Lyons,T. and French, J., Modafinil; The unique properties of a new stimulant. Aviation Space and Env. Medicine. 62, 5, p 432-436, 1991

French, J., Whitmore, J., P. Hannon, G. Brainard and Schiflett, S.A., Photic effects on sustained performance. submitted to Space Operations and Applications Research symposium, 1991.

Predicting fatigue degraded performance. Neville, K.J., Rowe-Halbert, A.L., French, J., Eddy, D.R. and Schiflett, S.G. Proceedings of the South Texas Symposium on Human Factors and Ergometrics, 1991.

Schiflett, S.G. and French, J. Integration and application of assessment methodologies. Biosciences Review, Rockville MD, 1991

French, J., Whitmore, J., Hannon, P, Brainard, G. and Shiflett, S., Photic Effects on Sustained Performance, Proceedings Space Operations, Applications and Research, Houston, TX 1991

French, J., Neville, K., Rowe-Hallbert, A., Eddy, D.E. and Schiflett, S. Predicting fatigue effects on performance. Aviation, Space and Environmental Medicine, Accepted December 1991.

Appendix 3 Milestones during the quarters

MILESTONES

1 Oct - 31 Dec 1990

PROGRESS: The final report of our Desert Shield data was made to the MAC surgeon general's office. Fatigue data from Desert Shield provided useful insight into operational fatigue evaluation and the utility of fatigue models. The principle investigator, became chairperson for the HFE SusConOps TAG permitting greater contact with tri-service fatigue investigators. The physiological data from Fatigue I study was determined (melatonin, cortisol, temperature data). Microsaint animation program was purchased and implemented into models of cognitive fatigue. Polyvariate equations of fatigue (combining temperature, composite performance and hours awake variables) were determined for 30 hours sustained performance. Predictions from the equations were made for an upcoming 36 hours awake study. The protocol for this second sustained fatigue study (Fatigue II) was approved. Data collection began for the Fatigue II study.

1 Jan - 31 Mar 1991

PROGRESS: Another interruption in MicroSAINT models of fatigue occurred during the final days of Operation Desert Storm. An improved operational study was designed to take advantage of the maximum flight hours and minimum crew rest experienced during Desert Storm by MAC air crews and data collection began. A preliminary report is due 60 days after the end of the study. However, data collection on Fatigue II was completed. Data sensitive to fatigue was again distinguished as reaction time or accuracy variables.

1 Apr - 30 June 1991

PROGRESS: Models of air crew fatigue were extracted from the literature. Although these models were designed for commercial pilots they are being modified to account for military air crew based on our Desert Storm. The HFE SusConOps TAG meeting was entitled Desert Storm I and tri-service investigators who evaluated data during the hostilities presented what was done. The next meeting, Desert Storm II will present the results of those studies. A meeting was held in Groton, CN with members of the Human Factors staff for the Naval submarine school to discuss similarities and differences in research techniques. Contacts were made there with a senior programmer from Micro-Analysis and Design (MicroSAINT, Co) and a physiologist from the Royal Navy submarine school interested in MicroSAINT models of fatigue. Common problems were discussed.

A simple C3 MicroSAINT task was designed and tested. The cir'adian aspect of our melatonin data seemed to improve the predictability of the fatigue equation. Adding this periodic variable to our equation generated a linearly degraded oscillating performance curve, accelerated at certain times of day by the

melatonin weighting (nocturnally) and slowed at other times (diurnally) by the melatonin weighting. Thus, fatigue scores can be obtained for accuracy and performance values by knowing only the number of hours awake and the time of day. A simple MicroSAINT equation was designed to incorporate the new equation and degrade our cognitive programs.

<u>1 Jul - 30 Sept 1991</u>

PROGRESS: A MicroSAINT model of Commit switch action for Weapons Directors onboard an AWACS aircraft was developed. The equation for composite reaction time was used to degrade the completion times for the average Weapons director. Also during this time a salivary assay was developed for Melatonin which will greatly facilitate the assessment of this important circadian marker. Future refinements in the equations will focus on improving the composite scores and on increasing the number of subjects in the fatigue model. Predictions will be made for 36 hour sleep deprivation performance and a study conducted to verify the accuracy of the models. Composite Accuracy variables will be added to the Weapons director MicroSAINT simulation to further "humanize" the model. Finally, a general fatigue equation will be developed that can be imported to any MicroSAINT simulation for testing.

Appendix 4 Consultation contacts during the quarters

1. Dr Gerald Chubb
   Assistant Professor
   Ohio State Univ.
   Department of Aviation
   2160 West Case Rd
   Columbus OH 43235

Dr Chubb is an expert in synthetic tasks analysis and performance simulations. He served as a visiting scientist during the summer 1991 and provided training consultation and advice on the performance models.

2. Dr Mary Winsborough
   Diving and Submarine Life Support
   ARE Alverstoke
   Fort Rd
   Gosport
   Hants P0122 DU England

Dr Winsborough is interested in fatigue models for submariners of the Royal Navy. She has extensive experience with MicroSAINT and mathematical models of fatigue. A 3 day meeting at Groton CN illuminated several common interests and goals.

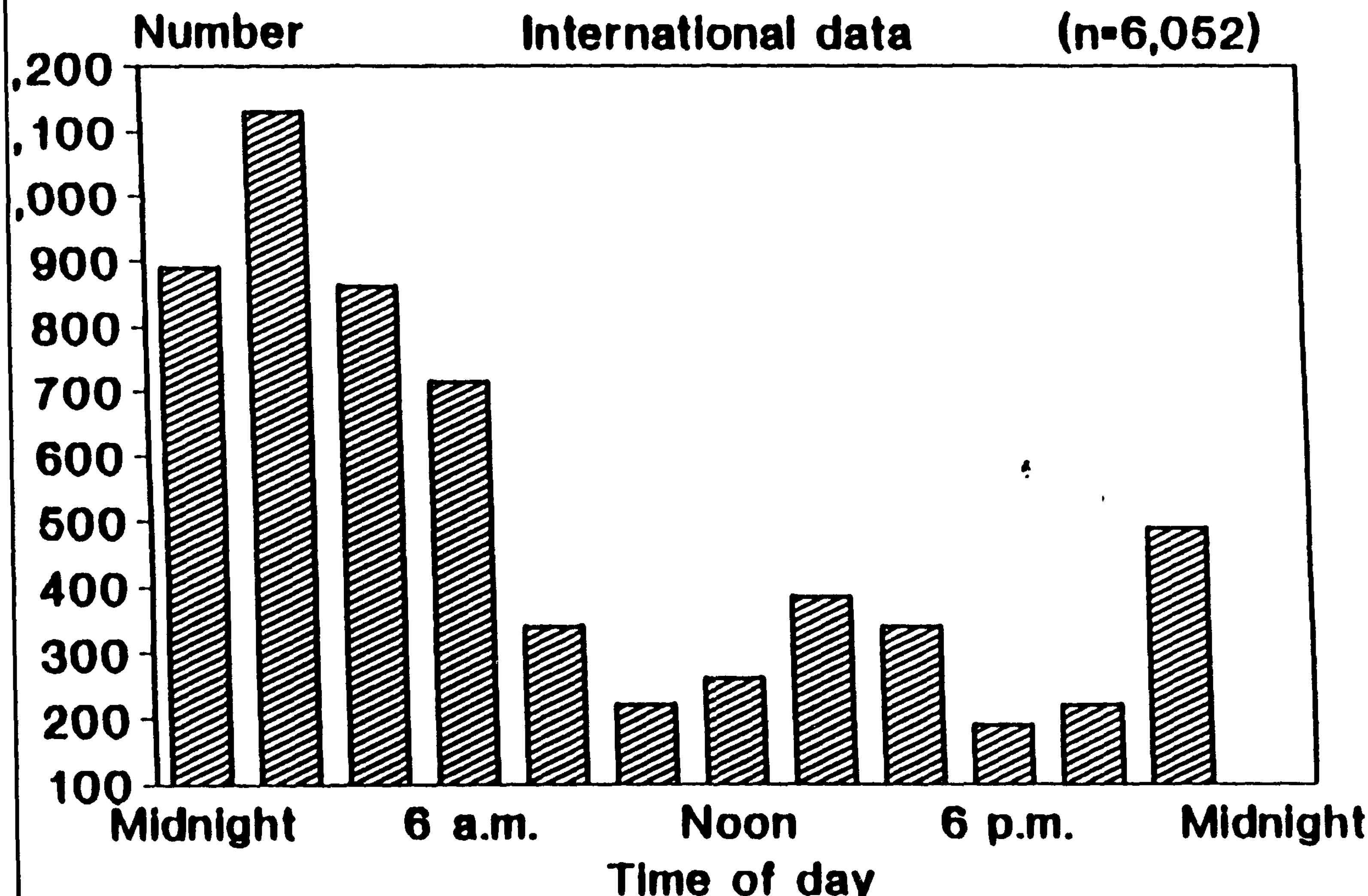
3. Mr Bill Griffith
   Micro Analysis and Design Co.
   9132 Thunderhead Dr
   Boulder CO 80302

Mr Griffith is a senior systems engineer for the MicroSAINT company. He attended the 3 day Groton CN meeting at the Submarine Base to discuss directions for fatigue models.

4. Margaret Bengry
   STI Signal Technology INC
   120 Cremona Dr
   PO Box 1950
   Goleta CA 93116-1950

Ms Bengry is manager, technical support. Attended a week long seminar describing the ILS macro-programming language for analysis of biological signals, particularly EEG. A rapid means to quantify EEG signals was developed.

–Fatigue-Related Vehicular Accidents

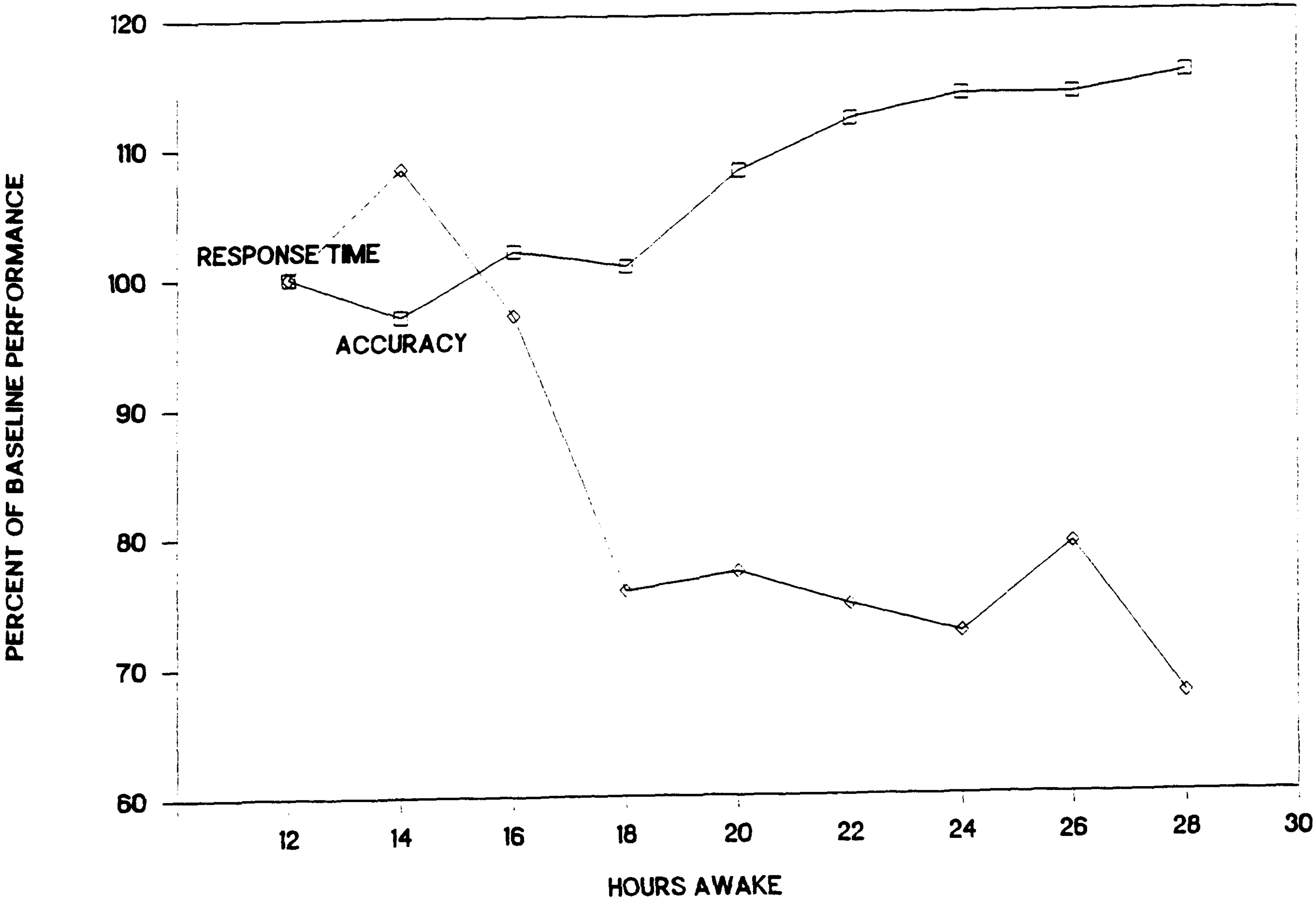


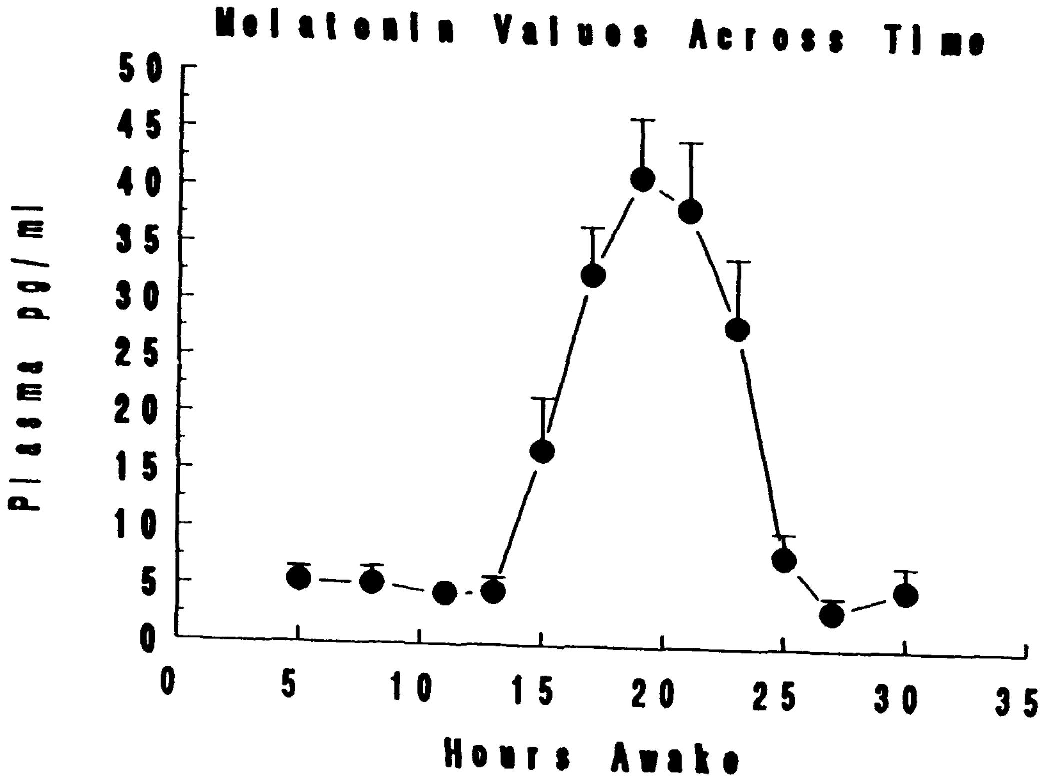
The distribution, by time of day, of 6,052 vehicular accidents that were judged by investigators to be fatigue-related.

SOURCE: M.M. Mitler, M.A. Carskadon, C.A. Czeisler, et al., "Catastrophes, Sleep, and Public Policy: Consensus Report," *Sleep* 11:100-109, 1988.

Response Time VS Accuracy

Numbers Test




Melatonin Values Across Time
Plasma pg/ml
50
45
40
35
30
25
20
15
10
5
0
0
5
10
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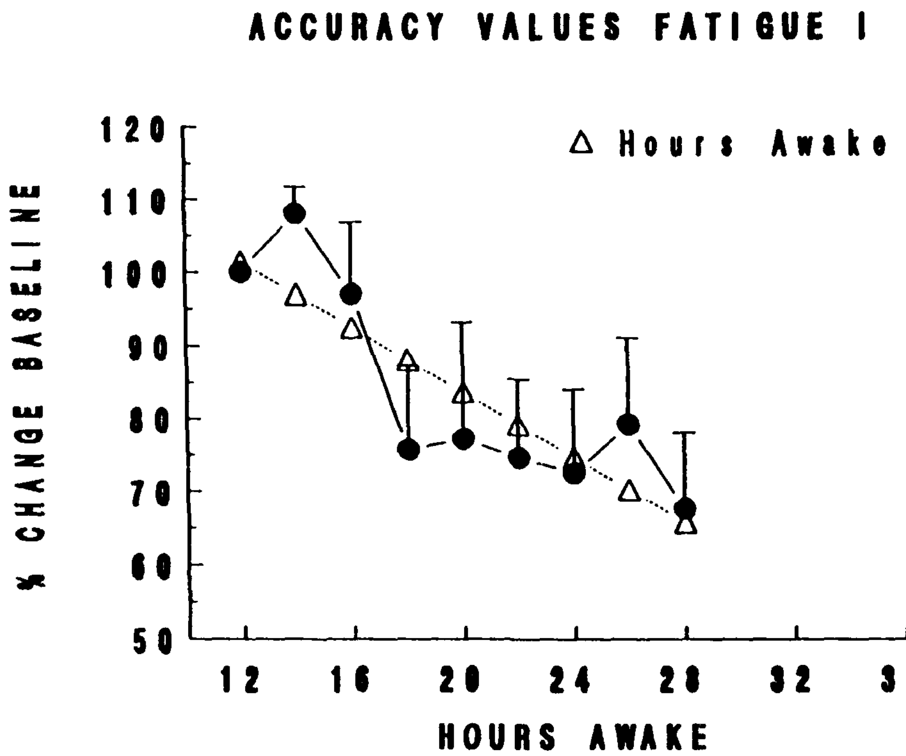
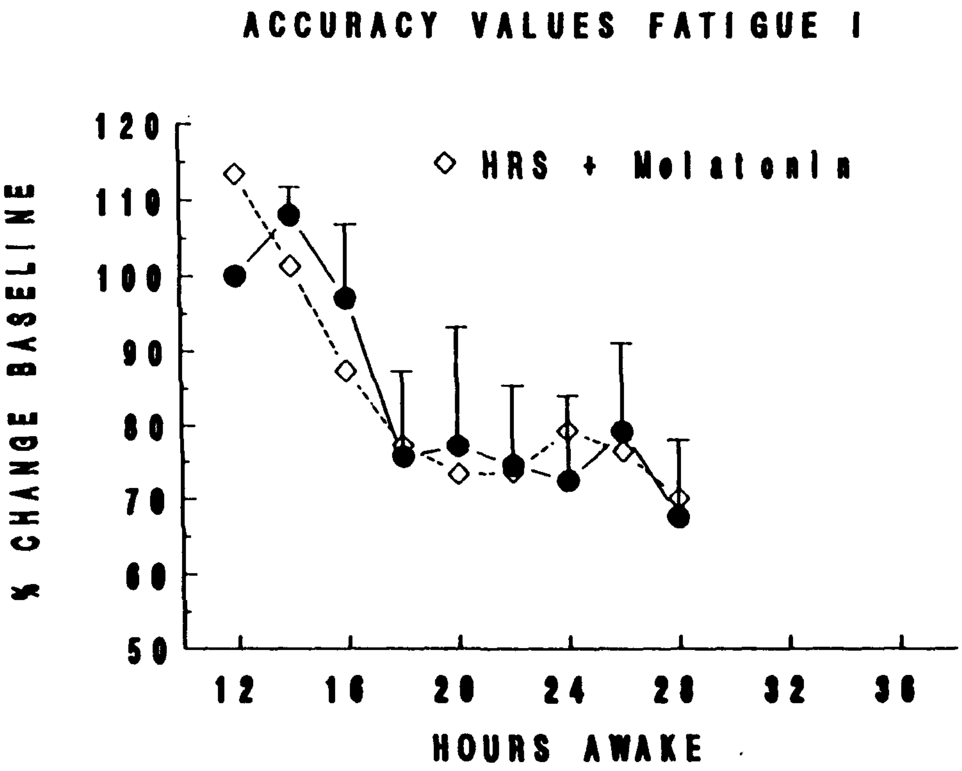
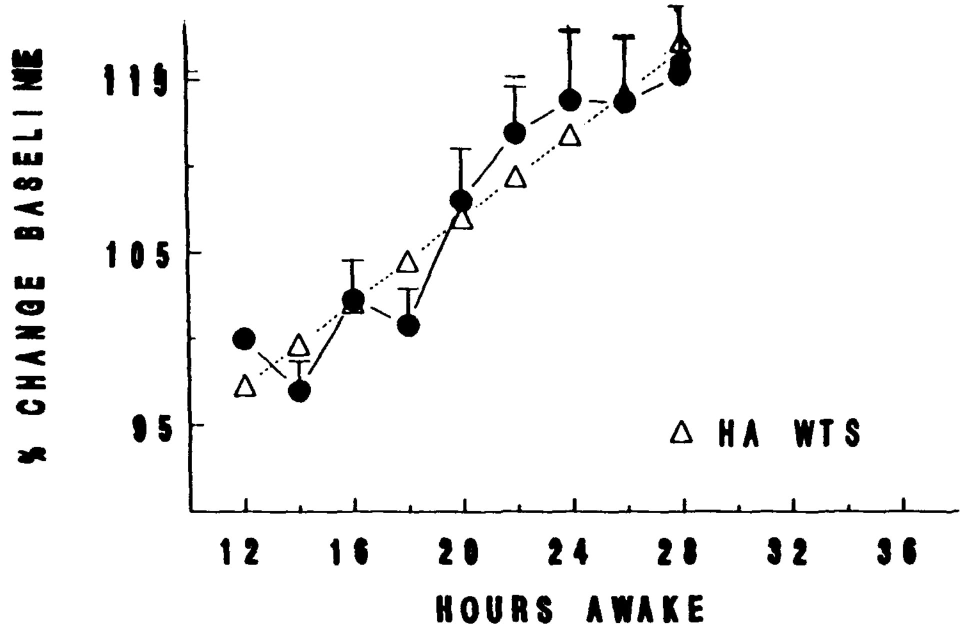
25
30
35
Hours Awake


ACCURACY VALUES FATIGUE I
Hours Awake
120
110
100
90
80
70
60
50
% CHANGE BASELINE
12
16
20
24
28
32
36
HOURS AWAKE


ACCURACY VALUES FATIGUE I
HRS + Melatonin
120
110
100
90
80
70
60
50
% CHANGE BASELINE
12
16
20
24
28
32
36
HOURS AWAKE

REACTION TIME FATIGUE I



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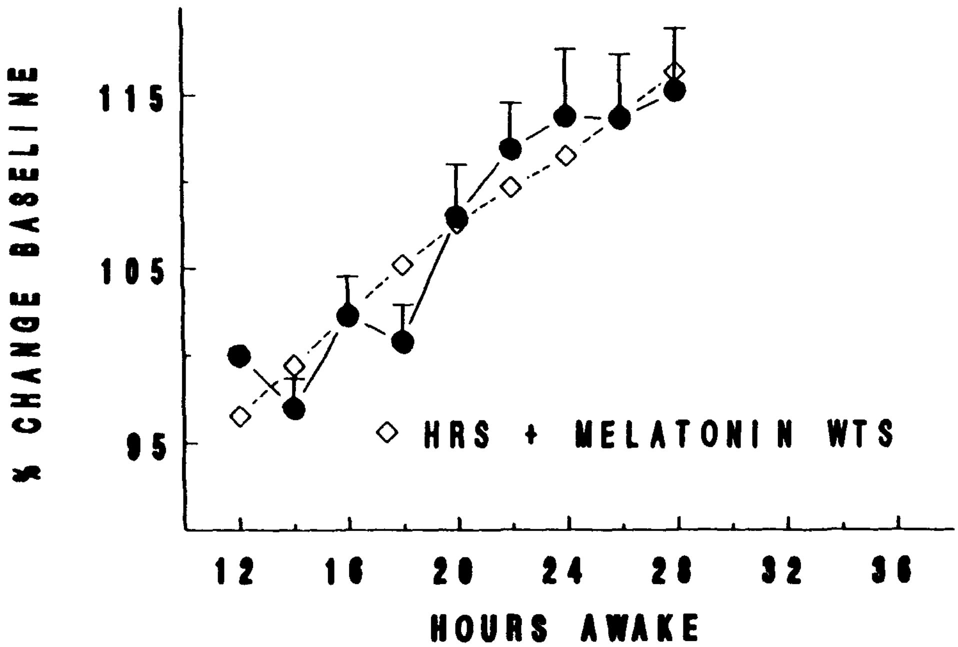
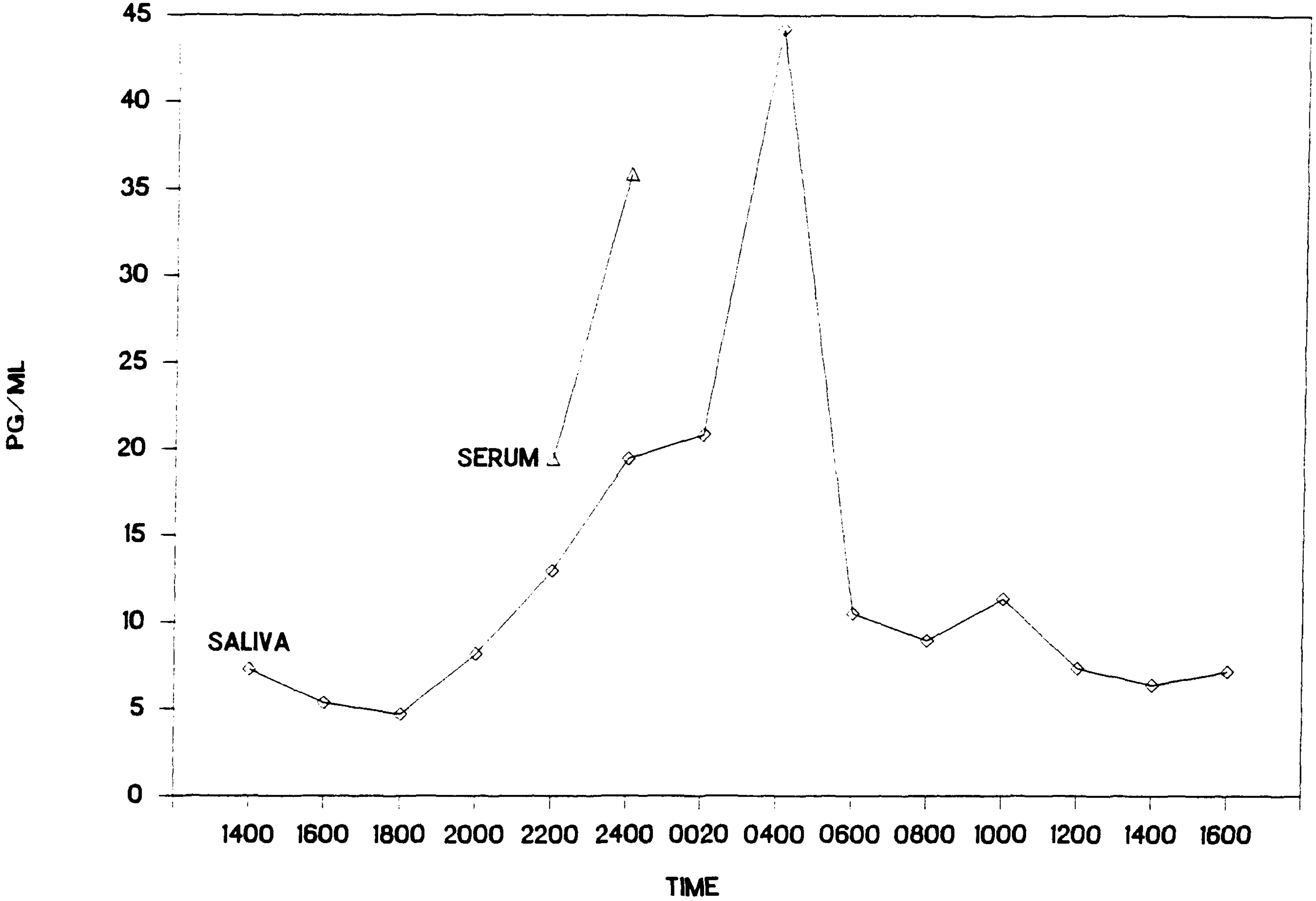


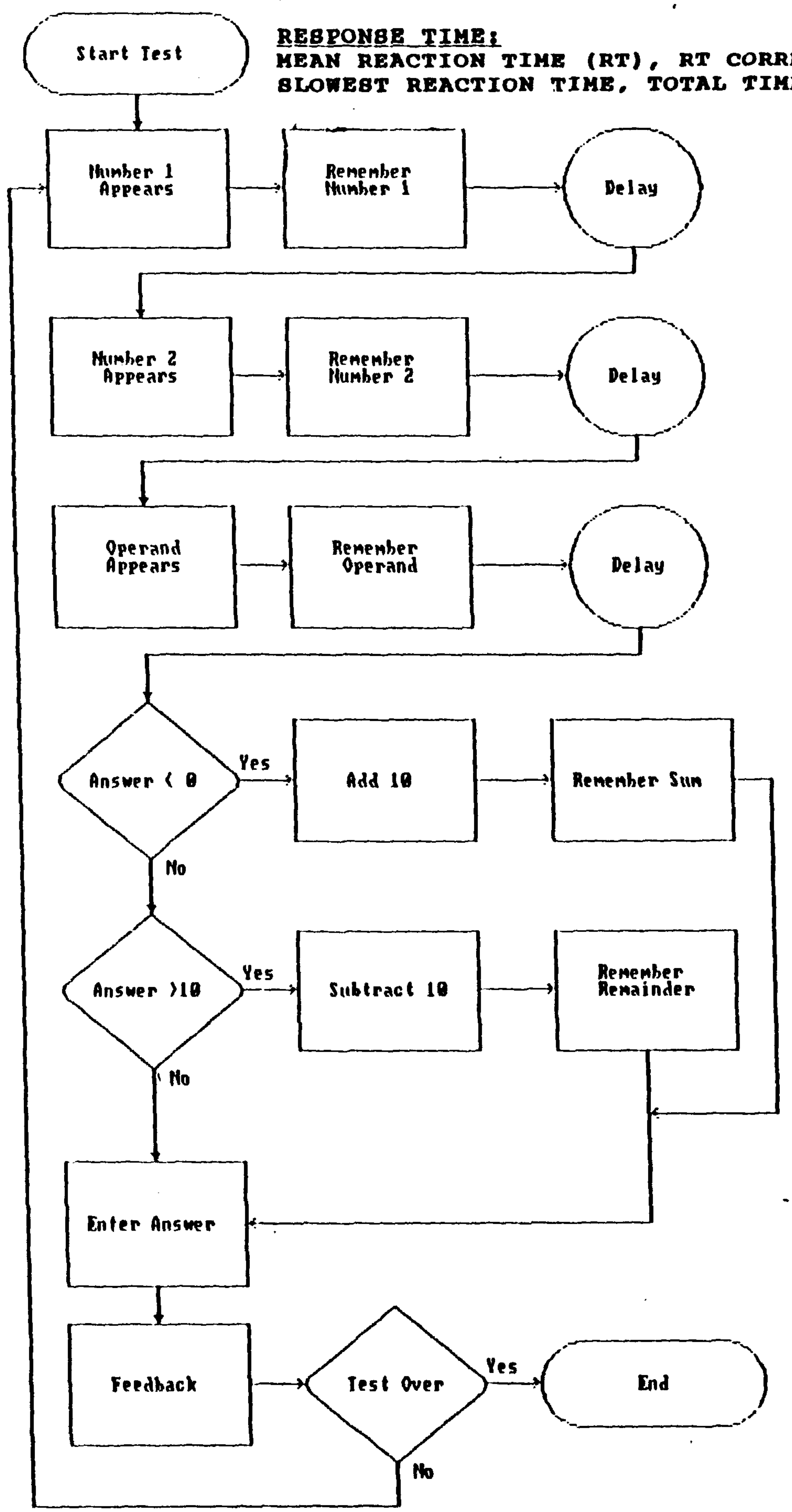
MELATONIN LEVELS IN SERUM AND SALIVA



SERIAL ADDITION-SUBTRACTION TEST : UTC-PAB

ACCURACY:
NUMBER OF ERRORS

RESPONSE TIME:
MEAN REACTION TIME (RT), RT CORRECT RESPONSES, SLOWEST REACTION TIME, TOTAL TIME TO TAKE THE TEST



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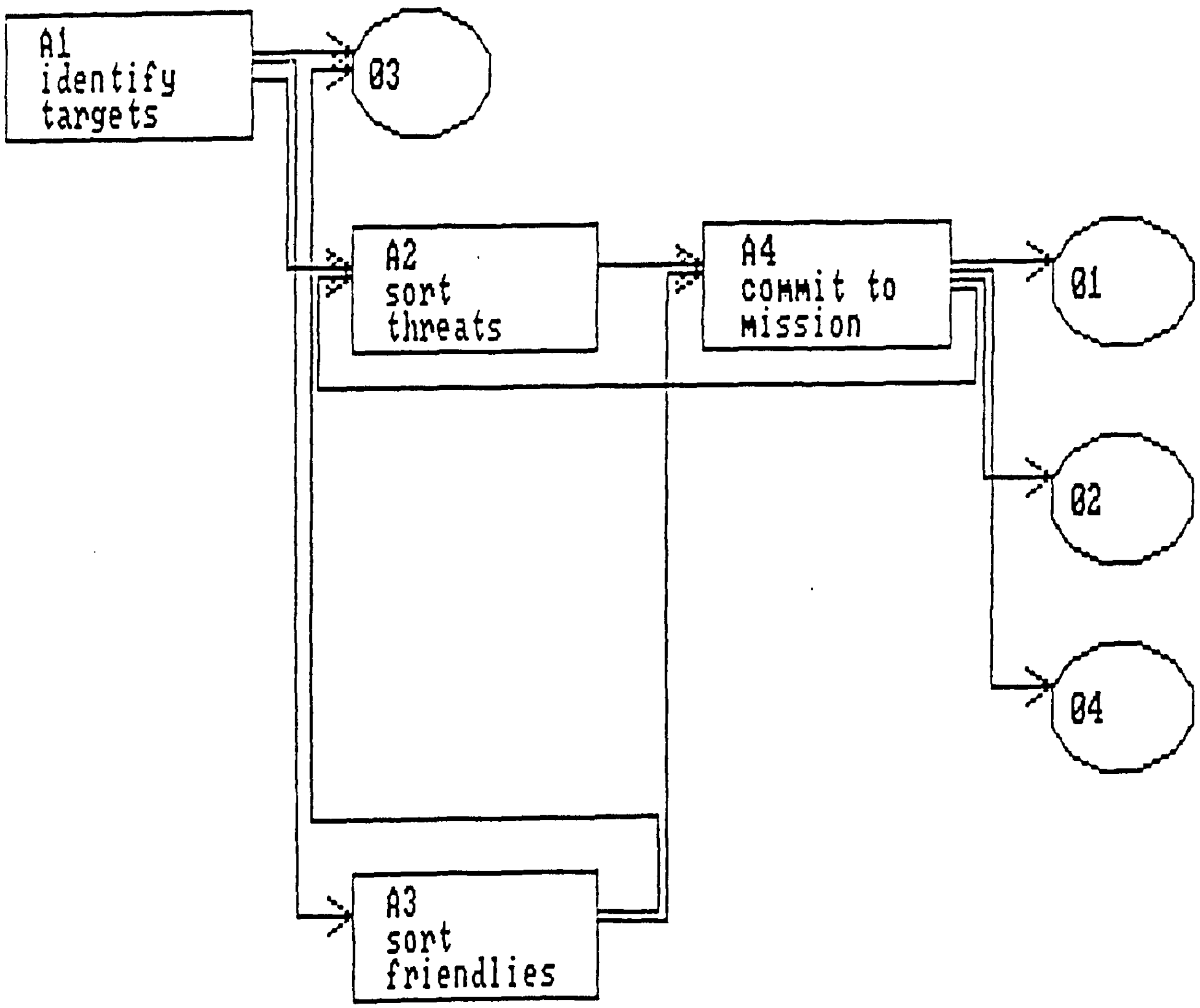

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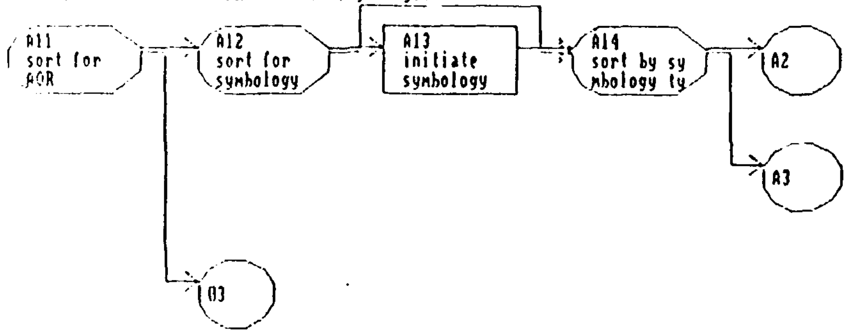

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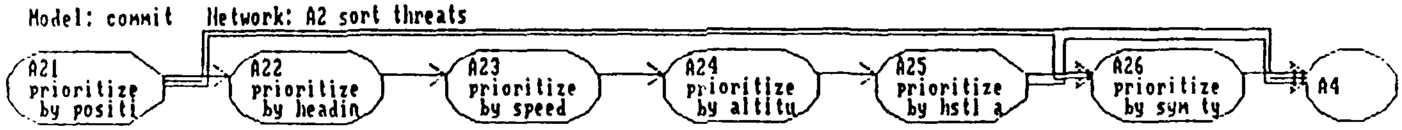

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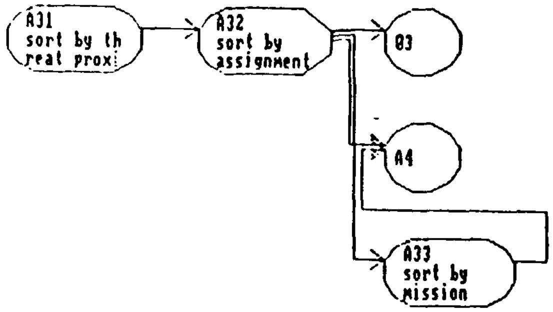

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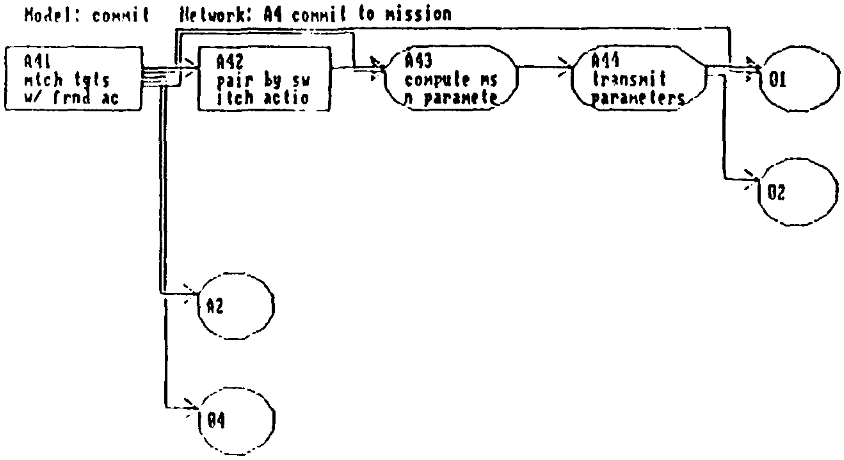

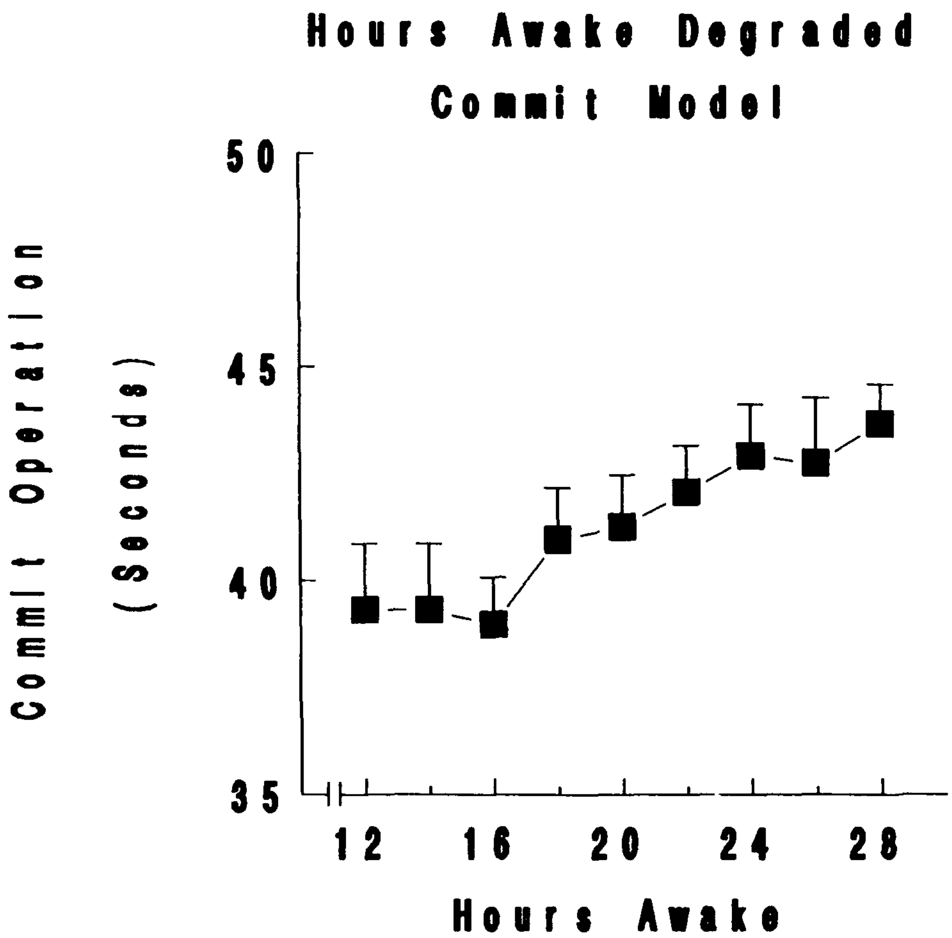
Hours Awake Degraded
Commit Model
Commit Operation
(Seconds)
50
45
40
35
12
16
20
24
28
Hours Awake